Washington and Oregon State - Adaptive Management Team

Resident Fish Literature Review

By: Dr. Mark J. Schneider

Draft

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Introduction

The supersaturation of surface waters with atmospheric gases (air) has long been recognized as potentially harmful to aquatic organisms (Gorham, 1901, Marsh and Gorham, 1905). The air gases, i.e., oxygen, nitrogen, carbon dioxide, argon and other trace gases will normally be found dissolved in near equilibrium with the ambient atmosphere unless influenced by physical or biological factors. These moderating factors include temperature, barometric and hydrostatic (depth) pressures, wind, solar input, organismic respiration and photosynthesis (Carroll and Schneider 2001). The physical status of dissolved gases is determined by Henry's Law, which simply stated says that the solubility of a gas in water (or tissue) is linearly related to the gas phase partial pressure (Colt, 1980). Understanding the implications of this gas law is essential to understanding the dynamics and effects of total dissolved gas (TDG) supersaturation on aquatic biota. Although there may be subtle differences in the degree of effects caused by organism exposure to TDG supersaturation all aquatic organisms will respond physiologically according to Henry's Law. Total dissolved gas pressure is the sum of the partial pressures of all the gases dissolved in water or aquatic organism tissues. The total amount of gas dissolved in water is the difference between the sum of all gases in water and the sum of the same gases in air, often expressed as percent saturation. When the partial pressure of a gas in water or tissue is equal to the partial pressure in air an equilibrium exists. When equilibrium exists there is no net flux of that gas either in or out of the water or tissue. If the partial pressure of a dissolved gas is greater than that of the gas in air, the water or tissue is supersaturated with that gas. Under such condition the gas will tend to diffuse out of the water or tissue until equilibrium is attained. In the case of an organism's tissues, the gases may diffuse out of the dissolved state to a gaseous phase and result in visible signs such as bubbles under the skin surface or tissue disrupting internal bubbles. This state is known as gas bubble disease (GBD)(D'Aoust and Smith, 1974, Weitkamp, 2007).

When the partial pressure of dissolved gas is more than the ambient pressure, the gas can move out of solution to the gaseous state. In an aquatic system such as a lake or river the most critical fact influencing ambient pressure is depth. Each meter of depth affects the solubility state of TDG by 10%. The effect of increasing hydrostatic pressure on the solubility of dissolved atmospheric gas is the critical factor in the concept of "depth compensation" for organisms residing in surface waters determined to be supersaturated at the surface. This means that the depth of a fish or invertebrate species determines the biological impact of exposure to water supersaturated with atmospheric gas. If the Columbia River is found to be 120% supersaturated at the surface the biological effective level of gas at 1 m is 110% supersaturation due to the compensatory influence of hydrostatic pressure. At 2 m depth the TDG is in equilibrium, i.e., it is no longer supersaturated. And,according to the gas law the same is true for fish or invertebrate tissue gas levels. To further illustrate the point let us assume that the tissues of an aquatic organism are saturated with the dissolved gases of the surrounding waters and the gas level is 120% supersaturated at the water surface. At a depth of 2 m or more the organism can not develop signs of GBD. In short GBD is the result of uncompensated hyperbaric pressure of TDG. Depth compensation is a critical factor that one must consider in evaluating the effects of TDG on Columbia and Snake river aquatic species. This fact is true for any body of water where organisms have access to depth. The Federal Columbia River Power System (FCRPS) reservoirs offer vast areas and volumes of water deeper than 2 m.

The primary purpose of this report is to review and evaluate the published scientific literature regarding the effects of TDG supersaturation on aquatic biota. In particular, this report will review recent literature and research findings regarding the effects of TDG supersaturation on resident fish and invertebrates. It should be noted that this report will not review the extensive literature addressing reactions and effects of TDG supersaturation on salmonids. Much of that material predated or was developed simultaneous to the series of Federal Columbia River Power System Biological Opinions (BiOp) and was incorporated there as appropriate.
This report will, however, briefly summarize the results of biological monitoring of TDG effects on the Endangered Species Act (ESA) listed salmonid stocks of the Columbia River Basin.

Detailed biological monitoring records may be found in the annual compliance reports to the Oregon and Washington water quality agencies (NMFS 1996-2001, FPC 2001-2007). The results of this extensive monitoring were collected under a wide variety of river freshet conditions, spill conditions (both voluntary and involuntary), levels of TDG supersaturation, and influences of environmental factors. Following a brief review of the salmon record this report will review and evaluate the relevant scientific literature discussing the effects of TDG on resident fish and aquatic invertebrates. Reflecting on the previous discussion of dissolved gas dynamics and gas levels it is reasonable to speculate that the biological record contained in the thirteen years of BiOp biological monitoring may serve as an indicator of how aquatic organisms, whether salmonid or resident fish or invertebrates, are affected by and respond to TDG supersaturation.

An assumption to be tested during the literature review is that all aquatic organisms; salmonids, resident fish and aquatic invertebrates, are similarly affected by TDG supersaturation and that these similarities reflect the basic laws of gas physics. Finally, the report will offer conclusions regarding the relevance of the resident fish and invertebrate literature to the Columbia and Snake river voluntary spill program under the ESA.

Biological Effects – Salmonids

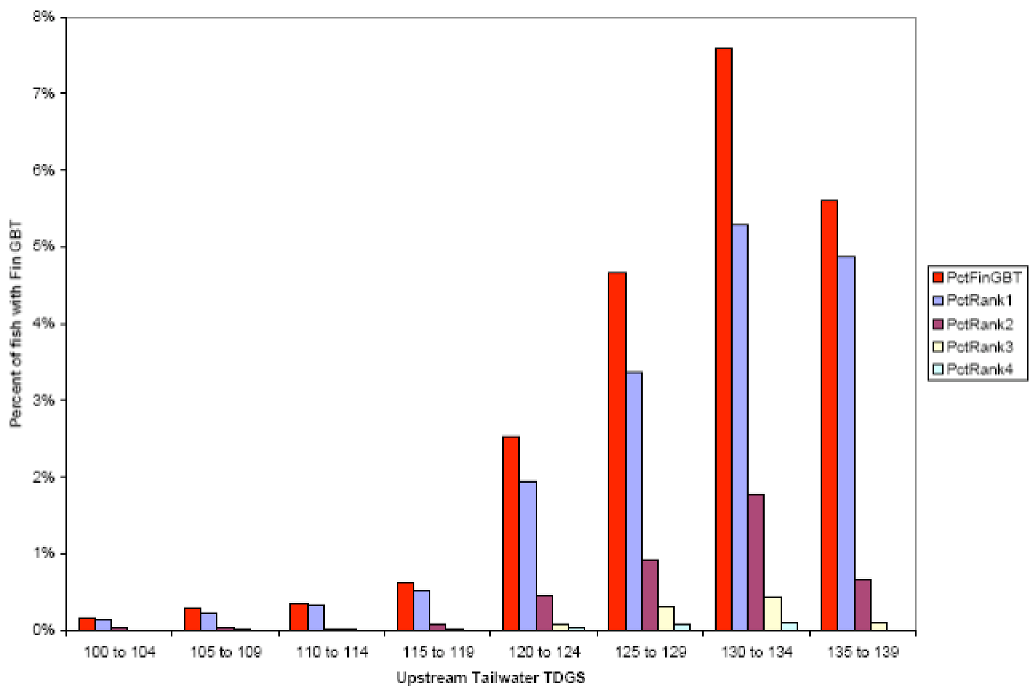
In 1995 the federal and state fish and wildlife agencies and the Indian tribes evaluated the relative risks to juvenile salmonids from voluntary spill induced gas supersaturation compared to the risks of passage through hydroelectric turbines (WDFW 1995). Their report concluded that the risk due to salmonid exposure to TDG in the range of 120-125% supersaturation was less than would be encountered by turbine passage at the main stem projects. Therefore, the report recommended adoption of voluntary spill limited by gas levels of 120-125%.

The 1995 National Marine Fisheries Service (NMFS) BiOp reflected the findings of the 1995 risk assessment and adopted a voluntary spill program as a main strategy to improve fish passage (NMFS, 1995). However, the BiOp established a more conservative limit to spill generated TDG, i.e., 120% instead of the 125% urged by the other fishery managers. The NMFS decision was based on findings published in the scientific literature and the guidance of a technical work group. The NMFS biologists concluded that salmonids could tolerate 120% TDG for a period equivalent to the migration period through the FCRPS, which is about 40 days, without suffering mortality.

The NMFS biologists recognized that the BiOp spill program would result in water quality exceedance of the Environmental Protection Agency (EPA) 110% TDG standard. Therefore, although the literature and the expert technical work group supported the decision to allow TDG from voluntary spill up to 120%, the NMFS staff also mandated biological and physical monitoring programs to serve as safegaurds in the spill management process. Physical monitoring of TDG provided real-time information on forebay and tailrace gas levels. The program is guided by voluntary spill curtailment at thresholds of 115% forebay and 120% tailrace TDG. The biological monitoring established conservative criteria of GBD signs which, if surpassed, would also result in spill curtaliment. Specifically, actions to reduce TDG level would be taken if 15% of the fish examined exhibited any bubbles on unpaired fins or 5% of the fish exhibited bubbles covering 25% or more of the surface of any unpaired fin. These action levels were deemed a conservative interpretation of literature findings which indicated that mortality did not occur until approximately 60% of sampled fish exhibited bubbles in fins or 30% exhibited bubbles covering 25% or more of an unpaired fin.

Since 1995, the biological monitoring program has recorded the annual effects of the FCRPS biological opinion voluntary spill program as well as the more severe TDG effects of involuntary spill. The overall number of juvenile and adult salmonids affected with GBD signs observed over the years through the biological monitoring has consistently shown very low incidence of

GBD when gas levels are at or less than the 120% tailrace criteria. When fish are exposed to gas levels greater than 120%, there is an increasing trend in incidence and severity of these signs (Figure 1). However, for all fish examined for signs of GBD through the thirteen years of the monitoring program, the incidence of fin signs observed was 0.5% when tailrace TDG levels were 120% or less, well below the NMFS prescribed threshold of 15%. These results demonstrate the minimal biological effect of BiOp spill levels managed to 120% in the project tailraces. The results also continue to validate the original assessment of the risks to aquatic biota of 120% TDG supersaturation. The monitoring program has also shown that the percentage of fish affected with GBD begins to increase when TDG rises above 120% and then dramatically increases when TDG rises above 125% (Fish Passage Center, 2006). Historically, these TDG levels have only occurred during involuntary spill and are unrelated to the BiOp spill program.



ram between 1995 and 2005 (red bar). Other bars (blue, brown, yellow, gray) display percentage of fish with Rank 1-4 levels of GBD signs. Fin ranks are: rank 1 – less than 5% fin area covered with bubbles, rank 2 – 5 to 25%, rank 3 – 26 to 50% and rank 4 – greater

than 50%.

Recent Resident Fish Literature Review

Exposure of resident fish to TDG supersaturation can result in development of signs of GBD. These include blisters or bubbles (emphysema) in the fins, mouth, and skin, abnormal protrusion of the eye (exopthalmia) due to a volume of gas forming behind the eyeball, and gas bubbles (emboli) forming in the circulatory system. The prevalence, severity and progression of GBD signs has been investigated by several laboratories and investigators (Bouck 1980, Cochnauer, 2000, and Antcliffe, 2002 and 2003). Although the majority of literature citations dealing with biological effects of TDG have focused on salmonids, there have been investigations of a wide variety of aquatic biota. Early studies dealt with determining gas tolerance thresholds. These studies found that there were species differences in susceptibility and sensitivity to TDG supersaturation (Fickeisen and Montgomery, 1978, Fickeisen and Schneider 1974, Heggberget, 1984). Most often when the mix of salmonids and resident species were involved in an investigation, salmon and trout species proved to be slightly more sensitive to elevated gas (Mesa et al. 2000, and Beeman et al. 2003). Abernethy et al. (2001) testing the effects of turbine passage pressure changes on previously TDG supersaturation exposed fish found that resident bluegill were more resistant to effects than rainbow trout or chinook salmon

Recently, studies were conducted with resident fish from Lake Roosevelt (Vanderkooi et al, Chapter II in Beeman et al, 2003). The species involved included northern pike minnow, walleye, two species of sucker and red sided shiner . Fish exposed to 125 and 130 % died without extensive development of signs. The progression of gas bubbles was unpredictable at any exposure level except 115%. However, there was little mortality observed in any of the species studied at gas levels below 120%. The investigators also suggested that in resident fish the prevalence and severity of signs is not predictive of mortality.

There have been a number of additional studies providing important findings for resident fish and aquatic invertebrates. The objectives of these studies were to investigate the impacts of TDG supersaturation on selected segments of Columbia River biota as well as to document the specific consequences of TDG exposure. Many of these studies revealed common findings allowing important general conclusions about dissolved gas effects and the thresholds for those effects. Ryan et al (2000) reported on four years of investigations during which resident fish and invertebrates were collected and inspected for signs of GBD. A total of 39,924 resident fish representing 27 species as well as 5434 invertebrates of 27 taxa were collected (Appendix A). The collection sites were of particular relevance to evaluating effects of the BiOp spill program since they were above Priest Rapids Dam and below Bonneville Dam on the Columbia River and Ice Harbor Dam on the Snake River. All of the resident fish sampled were collected in a narrow depth range of 0-3 m. Benthic invertebrates were sampled to a depth of 0.6 m. Ryan et al. recognized that any organisms collected below these depths would have benefitted from depth compensation and would have, therefore, been of questionable use in documenting impacts of TDG supersaturation effects. The field sampling was conducted during the each spring freshet (April through June) of 1994 through 1997. The TDG levels measured during the study reflected the runoff volumes. In years of exceptionally high gas, e.g., 1997, when TDG ranged from 120-130% TDG, the incidence of GBD commonly ranged from 15-25% of the resident fish examined. However, signs of GBD in fish were rare on those occasions when the TDG was less than 120%. It is worth noting this fact because the fish were collected in shallow water (0-3 m). therefore, the recorded incidence of GBD signs is not likely a good representation of population level effects since any fish residing deeper than 3 m were beneficiaries of depth compensation. Finally, with regard to aquatic invertebrates collected only seven individuals showed signs of GBD.

Cochnauer (2000) conducted extensive monitoring of resident and salmonid fish species in the lower Clearwater River and North Fork Clearwater River below Dwoshak Dam. Resident species included lamprey, whitefish and large scale sucker (Appendix A). Over 30,000 specimens were taken over a five year period. The TDG levels exceeded 110% for more than a month each year between 1995 and 1997. The incidence of GBD signs were less than 1% of the fish observed. Resident trout displayed the most gas bubble signs although some rank 1 signs were detected in whitefish and largescale sucker. The incidence of GBD diminished with distance from the spill and tailrace.

Weitkamp et al. (2003a and 2003b) published results of two resident fish studies conducted during the freseht and spill periods of 1998 through 2000. Both investigations were conducted on resident fish species in the lower Clark Fork River in northern Idaho. They recognized that supersaturation is a labile water quality condition influenced by pressure (hydrostatic and barometric) and other factors. Therefore behavior affecting fish depth likely plays a significant role in the potential for and the incidence and severity of GBD. During the study years fish were electrofished and collected by trapping in shallow water (0-2 m). The gas levels during 1997 reflected a near record runoff volume ranging from 143-158% TDG for over a month and remained above 127% for another month. The gas levels in 1999 were a little more moderate yet maintained a level between 120 -130% TDG for a month. In 1998 and 2000 runoff conditions were moderate displaying TDG near or slightly above 120% at times. In the first study Weitkamp radio tagged fish from seven species including for different trout species, suckers, mountain whitefish, and northern pike minnow. The depths of the tagged non-trout species were found to average more than 2.0 m. The trout species average median depth was 1.5 m, cutthroat was 1.8 m. These are all depths offering compensation for TDG levels of approximately 120%. Reflective of this point the incidence and severity of GBD in collected fish were low.

The second Weitkamp study of resident fish species of the Lower Clark Fork River focused on the incidence and severity of GBD. A total of 16 species of fish were collected (Appendix A). The most abundant species were brown trout, 3 species of sucker, northern pike minnow, and peamouth. As in the previous study the fish were caught by electrofishing in waters less than 2.0 m deep. The years of the study and TDG conditions were reported in the previous paragraph. Captured fish were examined for GBD signs promptly following capture. In addition, rainbow and cutthroat trout were subjected to TDG exposure in 2 m deep live cages held in the river water. In these tests all fish died within four days of exposure to 140% TDG. There was less mortality following 15 days exposure to 123-138% TDG. By comparison other trout held in 9 m deep live cages experienced no mortality following two weeks at 125%, further there were no GBD signs in these fish. Weitkamp et al (2003b) concluded that few resident fish displayed GBD signs when exposed at 125-130% TDG. As in the previous radio tag studies the investigators attributed the results in their study to depth compensation. The 9 m depth live cage studies also supported their conclusion. Both the incidence and severity of GBD signs in these tests were less than might have been expected based on earlier laboratory investigations. Therefore, the authors urged caution in making conclusions about impacts to aquatic life exposed to TDG levels as conventionally measured at the surface of the water.

Canadian investigators Antcliffe et al (2002 and 2003) conducted studies of GBD by exposing rainbow trout to 110, 114, 116, 122, and 140% TDG. Fish were held in shallow 0.25cm deep tanks, in the laboratory. The 50% mortality occurred in slightly more than five hours at the highest gas level, 140% TDG.   All fish exposed to 114% survived for nearly a week. When the test fish were exposed to 122% TDG in 2.5 m deep volitional tanks all fish exposed survived. The authors concluded that strict adherence to 110% Water Quality Act criterion where water depth allowed fish to escape to a compensatory depth may not be necessary.

In 1993 salmonid and resident fish and invertebrates were collected from a 170 km stretch of the Columbia river below Bonneville Dam (Toner and Dawley, 1995). Dissolved gas levels in the river during the sampling and collection period reached 128% on four days and mean values above 120% were sustained for nine days. A total of 4,124 biologic specimens were collected including 2,405 salmonids, over 1,500 resident fish and nearly 70 invertebrates including clams, crayfish and insect larvae (Appendix A). Even though the TDG levels during the sampling period were high, the incidence and prevalence of GBD signs were minor. Gas blisters between fish fin rays affected 1-3% of the salmonids inspected. Body blisters and exophthalmia were observed in a low percentage (< 10%) of the resident fish species. No signs of GBD were found in the invertebrates sampled (clams, crayfish and insect larvae).

During a high spill period in 1994, a team of investigators monitored GBD in juvenile salmonids, resident fish and invertebrates below Bonneville and Ice Harbor dams (Toner et al,1995). They also collected specimens for inspection above and below Priest Rapids Dam.. Over 18,000 specimens were collected and examined (Appendix A). Included were nearly 2,100 juvenile salmonids, 12,000 resident fish and over 4,100 invertebrates. GBD signs were common in organisms collected below Ice Harbor where the TDG levels reached 136% on three days and were more than 130% between 7-11 hours each day of the study period. Gas bubble disease signs were observed in 5-10% of the 22 resident fish species captured. When TDG declined to an average 110% with occasional spikes near 115% no GBD signs were found at any site. Signs of GBD were observed in only one fish species captured below Bonneville and Priest Rapids dams and in no fish above Priest Rapids Dam. However, TDG was not measured above 120% at the monitoring site although it did occasionally exceed that level in mid-river. Only one species of cladoceran displayed GBD signs in the invertebrates and only at Ice Harbor Dam. the important point of these findings is that GBD was found at gas levels in the mid-130% range. When TDG was less that 120% signs of GBD diminished and in most cases were absent

In a study of sublethal effects of TDG supersaturation, declining food consumption was correlated with increasing TDG in northern pike minnow (Bentley and Dawley 1981).   The weight of food consumed by the laboratory tested fish was halved at exposures to 117% TDG and reduced by an additional third at 120%. However, their field studies indicated pike minnow may not be significantly stressed by supersaturation between 117 and 145.1% TDG. Fish captured in gill nets during these gas levels revealed no GBD signs.   However, it should be noted that the capture depth of these fish likely exceeded three to four meters. Reflecting back on the discussion of gas laws and depth compensation, any aquatic species at a depth of 3-4 m would be protected from GBD by the hydrostatic pressure to 130-140% TDG as measured at the water surface.

Studies of potential effects of gas supersaturation on fish behavior are relatively rare. Backman et al (1991), however, attempted to determine whether or not changes in behavior or survival of a migratory fish species might result from exposure to TDG supersaturation. To this end the investigators exposed sub-yearling American shad to five levels of gas supersaturation between 101-128% for four hours. GBD signs were detected in fish tissues at the highest gas level. However, no behavioral effects that might affect survival during migration was observed.

A frequently asked question in discussions of TDG supersaturation concerns the ability of fish to detect significantly elevated gas saturation levels and to take mitigative behavioral action. Although there is no definitive answer, the investigations by Chamberlain et al. in 1980 are of note. The juvenile Atlantic croaker had been observed to rise vertically in 2.5 m tall water column when exposed to acute gas supersaturation at 145% TDG. Subsequently, the exposed croaker specimens were observed to swim to a depth restoring neutral buoyancy. The croaker is a physoclist, i.e., this species has no pneumatic duct connecting the swim bladder to the gut which means they have no anatomical means of venting a buoyancy upsetting increase in swim bladder gas that may result from supersaturation exposure. The fish's observed rise in the water column may reflect such a distention of the swim bladder with no immediate means to relieve it. The croaker's subsequent voluntary sounding to depth would not only return it to neutral buoyancy but provide depth compensation and avoidance of GBD. Chamberlain et al developed a nonlinear response model based on this hypothesis.

Investigators Schrank et al. (1997 and 1998) evaluated the effects of dissolved gas supersaturation on fish and invertebrates at several sites in the FCRPS during the two years of BiOp spill. Specimens were collected by electrofishing and beach seines from below Ice Harbor and Bonneville dams and from below and above Priest Rapids Dam. Throughout the study approximately 1,200 salmonids, 16,000 resident fish and 1,300 invertebrates were evaluated. At the time of sample collection organisms were examined for GBD signs, including emphysema of the fins, head, and body surfaces as well as for exophthalmia. Organisms were then held for four days and examined again for prevalence and severity of GBD. Salmonid and resident fish were also held in a series of net pens. The enclosures provided extended exposure of test organisms to river water quality conditions at different depths to test the effects of depth compensation. The net pens were held at 0-0.5, 2-3, and 0-4 m depth for a period of four days at which time the occupants were evaluated for GBD signs, incidence and severity. The results of the two years of study are summarized in Table 1. The major findings included GBD signs observed at the time of capture tended to worsen during the holding period, particularly if the organisms were held near the surface. GBD prevalence in captive resident fish held in the 0-4 m deep net pens was higher than the level of GBD seen in the same species collected from the river at that time. Similarly, mortality of chinook held in the shallow pens ranged from 58-100%. Yet, chinook mortality for fish held in the 0-4m pens ranged from 1-84%. Schrank et al concluded that mortality rates of salmonids and the prevalence and severity of GBD signs in the resident species was not representative of river fish because of duration of exposure and depth compensation pertaining to the fish population at large.

Conclusions

- The BiOp physical monitoring program has proven capability for management of voluntary spill to 120% TDG.
- The BiOp biological monitoring has demonstrated the validity of original and subsequent risk analyses regarding 120% TDG.
- Monitoring results and scientific literature reveal GBD signs incidence and severity begin to increase above 123% TDG. Mortality is more likely above 130% TDG.
- The incidence and severity of GBD signs in all fish (salmonid and resident) and aquatic invertebrates is a function of gas supersaturation level, duration of exposure and depth of exposure, and the difference between tissue gas partial pressure and the ambient gas partial pressure.
- Multiple literature citations discussing laboratory and field studies concluded negligible adverse effects of 120% TDG exposure of resident fish and aquatic invertebrates.
- The concept of "depth compensation" is pivotal to understanding the TDG issues of the Columbia river. The explanation for these results lies in the extensive amounts of deep water habitat available in the FCRPS reservoir pools and the compensatory effects to organisms utilizing this habitat.
- With voluntary spill limited by 120% TDG only the top one meter of the river exceeds the EPA standard of 110% TDG.
- The review of resident fish and aquatic invertebrate literature validates the assumption made in the introduction.i.e., all aquatic biota, salmonids, resident fish and invertebrates are all similarly affected by TDG supersaturation.
- Resident fish having access to deep water habitat utilize this habitat as part of their normal behavior. This behavior provides these organisms with hydrostatic derived compensation to TDG supersaturation.

Table 1. Summary of Schrank et al,1997 and 1998					
Study year & location	**TDG Levels Reported**	**GBD % Incidence**		**Net Pens-% Incidence of GBD Signs & Mortality**	
<u>1995</u>			**0-0.5 m deep**	**2-3 m deep**	**0-4 m deep**
IHR tailrace	130% for 6 weeks. 138% peak	16.5 bass, 13.6 crappie 11.8 bullhead	97 resident sp 80 chinook. Highest mort.	40 resident sp 6 chinook. Lowest mort.	37 resident sp 52 chinook. 2nd highest mort.
	115-125%	9.4 peamouth 23.5 pikemino 16 sucker 3.5 cladoceran			
PRD reservoir	118-125%	5 resident sp 5.6 sandroller 4.8 sculpin			
BON tailrace	114-125% for 4 months	single sculpin & stickleback			
<u>1996</u>			**0-0.5 m deep**	**2-3 m deep**	**0-4 m deep**
IHR tailrace	Daily peak 130% for 10 weeks. 142% maximum	11-22 for 6 spp			Ranged 0-86. Mortalities ranged 0-4%
PRD tailrace	130% peak. above 120%for 2 months	2.8 salmonids 6.5 resident sp			
PRD reservoir	136% peak. above 125% for a month	26.6 suckers 6.9 chiselmout 5.9 pumpkinsd 5.9 stickleback 16.7 bluegill 15.6 sculpin			Ranged 0-70 Mortalities ranged 0-33%

		BON tailrace	120-140% for 2 months	Low incidence in resident spp 3.3 suckers 3.4 pikemino 3.4 sculpin 2.5 red side shiner			Ranged 0-58 Mortalities ranged 4-33 %

Appendix A. Literature Review of Resident Fish and Invertebrates April 24, 2008

Species		Exposure				Effect		Assessment and Citation
Common		**% TDG**	**Duration**	**Depth**	**Temperature**	**Lethal**	**Sublethal**	
Bluegill, fall Chinook, rainbow trout		100, 120 &135%	16-22 hr	0 & 30’	17^{o}C	Time to death		Resistance to TDG = bluegill > fall Chinook > rainbow trout. At 120% 14% trout died, all Chinook and bluegills survived showed few external signs. (Abernethy *et al*, 2001)
Rainbow trout		144, 122, 116, 114, & 110%	LT_{50}	0.25 & 0-1.0 m	10^{o} C	Time to death		LT_{50} = 5.1 hr at 140%, 55 hr at 122%, 9 dy to 42% mort at 116%. All survive at 114 & 110%. (Antcliffe et al, 2202 and 2003)
American shad		101, 111, 118, 124, & 128%	4 hr	15 cm			13 behavioral indicators observed	Behavioral tests (Bachman, et al, 1991) No GBT signs after 4 hr at 128%. No effect of TDG on behavior
Northern Squawfish (aka Pikeminnow)		100 -126 %	12 dy	0.25 m	Field tests, variable			32% died within 12 dy at 117% , 20 hr at 126%. Food consumption decreased between 100-126%. Field samples showed fish not seriously affected at 117 – 141%. Fish were below 3m depth. (Bentley, *et al*, 1981)
Suckers (3 spp), Northern. Pikeminnow, walleye		125 – 130%		Variable See Assess.	Field tests, variable			8000+ resident fish examined for GBD signs. Depths recorded above. Time to LT_{50} was 2x long at 125 as at 130%. Sensitivities at 125 & 130% were pikeminnow/lrg scale sucker.\>longns sucker>redside shiner>walleye. Walleye growth greater during year of high gas. Other spp growth unaffected. (Beeman *et al*, 2003b)

Channel catfish, bluegill sunfish		Diel fluctuation from 91/98% to 105/123 %	TDG fluctuations due to local heating					Fish tolerated the fluctuations in TDG by sounding in the ponds. The authors also observed that the increased TDG tolerance may have been due to an increased O_2:N_2 partial pressure ratio known to benefit the exposed fish. (Boyd *et al*, 1994)
28 spp.of resident fish, 39,924 specimens. 27 spp. of invertebrates, 5,434 specimens		River TDG = @ 110-145%	electrofished netpens= 4 dy	Fish =0-3 m, Varied depths Inverts= <0.6 m	unrecorded	Unable to correlate GBD sign prevalence and severity with mortality	See Figures 3-7 for GBD signs related to sample location	During 1994-97 freshets surveyed and held resident fishes and invertebrates GBD signs were rare when TDG <120%. Authors concluded 115/120% levels of waivers were of little –no detriment to nonsalmonids fishes . However, suggest that a change in waiver to exceed 120 % would result in increased prevalence of GBD. (Ryan *et al*, 2000) 5
Over 30,000 resident fish specimens examined. Lamprey, mnt whitefish, lrg scale sucker		Recorded only as above 110% or above 120%	Unknown	Unrecorded. GBT found to 12 mi below DWK	Unrecorded			GBT Incidence never exceeded 1% of sample. Samples in 1995, 96, 98 & 99- 0 to 0.2% with GBT. Only 1997 showed GBT @ 1% of sample. TDG exceeded 120% in 1997. (Cochnauer, 2000)
White sturgeon larvae		118 & 131%	10 & 13 dy	Maximum depth was 25 cm	14-16℃	50% mort at 131% TDG after 13 dy.	No morts at 118% TDG after 10 dy	Most of 50% mort at 131% TDG occurred after 4 dy. (Counihan, et al, 1998)
Atlantic Croaker, Juvenile		166 % N_2 73 % O_2 145 % TDG	< 1 day	Up to 2.5 m,	22°-27℃	One mort. After 3hr exposure All others survived	See Comments	Supersaturation of either N O, or air resulted in behavioral response. Intensified with increasing gas. Fish became buoyant. Mort died without external GB signs. (Chamberlain et al, 1980)
Mnt whitefish, cutthroat, lrgscal sucker, torrent sculpin		132% ± 3%at surface	10 dy	Controlled, live car. 0.31, 0.65, 1.0, 1.38, 3.2 m	10.0±0.5°C	See Assessment	See Assessment	Whitefish LT50=50 h@120%, 48 h@116%; cutthroat LT50= 34 h@120 %, 89 h@ 116%; sucker LT50= 103 h@120%, all survived at 116%; sculpin LT50= 10 dy@128%, LT50 not found at other TDGs. (Fiskeisen & Montgomery, 1978)

Carp, black bullhead		Bioassay exposure tanks ranging from 110-158% TGP	Up to 500 hr	30 cm	19.5±0.5°C	Carp 96h $LC_{50=}$122. 5.5% TGP Bullhead 96 h LC_{50}=114± 8.0% TGP		**Note: gas measurements reported in total gas pressure, not % saturation.** Author reported Fickeisen found no carp 96 hr morts at 135% TGP. Bullhead 96hr morts ranged from 124.4 to 126.7% TGP. . Gas saturation levels were determined by somewhat unorthodox method., ie, gas tight syringe, gas stripped and GC'd. (Gray, et al, 1982)
Sea bass, striped mullet		Bioassay exposure tanks ranging from 160-190 % TGP	Up to 96 hr	20 cm	20 and 26˚ C	Post larval sea bass 96hr LC_{50}=127. 2% TGP, mullet = 129.4% TGP. Fingerling LC_{50}=116. 0 & 124.8% TGP		**Note: gas measurements reported in total gas pressure, not % saturation.** Post larvae 96 hr LC $_{50}$ as 127.2% TGP for sea bass and 129.4% TGP for mullet. 96 hr LC_{50} for fingerlings were 116.0% TGP for sea bass and 124.8% TGP for mullet.). Gas saturation levels were determined by somewhat unorthodox method., ie, gas tight syringe, gas stripped and GC'd. (Gray et al, 1985)
Carp, black bullhead		100%, 114%, 120%, & 146% TGP	Up to 48 hr	unknown	19.5±0.5°C	Some mortality during experiment	See Assessment	Behavior of fish in a chambered tank receiving gassed water and control. Species behavior differed. Only a few Black bullhead remained in the 146% TGP for 6 hr. Carp. Most left. Carp showed less ability to detect and avoid gas. Detection and avoidance is species and site specific and varies with conditions. (Gray, et al, 1983)
Carp, black bullhead		110-180% TGP		unknown		Measured 96 hr LC_{50} under lotic conditions	See Assessment	Compared the 96 hr LC_{50} to previously determined times. Carp are more tolerant to TGP that bullhead. Eample-at 125% TGP all bullhead survived for 17 hr under lentic and 6 hr lotic. All carp survived for about 45 and 100 hr under both conditions. (Gray and Page 1983)

Catfish								Citation discussed the design and construction of degassing units for hatcheries. The introduction of the paper gives a very clear explanation for why dissolved gas supersaturation can be a problem and how the differential of TDG across a biological membrane can be a problem or not. (Hargreaves and Tucker 1999)
Brown trout, eel, perch,		100% - 200% TDG	Surface and 3m cages		At 180% all trout died in 3 hr, perch in 24, eels showed some bleeding			Brown trout were the least, eels the most tolerant. Only fish near the surface were killed while fish at 3m depth were mildly affected. (Heggberget, 1984)
Smallmouth bass, northern squawfish		125-130%	Unknown, fish caught in field	River temperature				Presence of GB observed in 179 bass and 85 squawfish during freshet when TDG exceeded 115%. (Montgomery & Becker, 1980)
Smallmouth bass		130%						Adult smallmouth bass survive more than 24 hr but less than 96 at 130%. (Fickeisen unpublished data). Bouck et al, 1976reported similar findings for largemouth bass.
Northern squawfish		125-135%		1 week				GBD observed after one week exposure to 125-135%. Similar reaction to that of salmon and steelhead (Bentley et al, 1976)
White bass, bluegill, largemouth bass		@105-121%	Individual fish exposure unknown		Seasonal averages variations of @8-18°C.			TDG levels in the power plant cooling water discharge canal were elevated by heating the water. When water temps remained high (118-121%) GBD peaked. GB signs absent or infrequent until TDG exceeded 115%. Lake Norman, Duke Power's Marshall Power Station, North Carolina. (McInerny, 1990)

Invertebrates (one each bristle worm & mayfly) unnamed resident fish spp		103 to 127% , max TDG recorded = 134%			Unrecorded in reference publication			One specimen each of bristle worm and mayfly with signs. Comprised 0.02% of 9,885 invertebrates examined. 2,134 resident fish examined during spring spill (103-127% TDG) No GB signs. Summer spill produced 160 resident fish out of a total 866 sampled showing GB signs, TDG = 134% peak TDG. (Parametrix, Inc. 2002)
N Pikeminnow, longnose sucker, walleye, rainbow trout		1996= 110-128% 1997=110-133%	Season-long study	Seasonal temps			No sublethal effect of TDG. Comparison of growth. Found no evidence	Study objective=to determine if elevated TDG affected growth. Although TDG exceeded 115% in 1996 May to early July. TDG conditions worse in 1997, exceeded 120% from May 11 to July 4, 1997. There is little effect on growth due to TDG (Maule, et al, (2003).
Black Crappie Bluegil Brown Bullhead Channel Catfish Chiselmouth Common Carp Fall Chinook Kokanee Largemouth Bass Mottled Sculpin Pumpkinseed Rainbow Trout Northern Pikeminnow Bridgelip Sucker Largescale Sucker Steelhead Smallmouth Bass White Crappie Mountain Whitefish Yellow Perch		90-140%	Field sampling precludes knowing the period of exposure. However, TDG was measured at the beginning and end of electrofishing transects.	Depth of fish capture was not reported. The electrofishing method usually precludes capture of fish deeper than a meter.	2^{o} C to 19^{o} C.			20 spp of fish were collected and observed for GB signs. Fish sampled when TDG levels were less that 120% did not show GBT. Fish sampled when TDG levels were grater than 125% did show severe GBT. 307 fish of 3012 showed signs. **Showed no signs**=fall Chinook, kokanee, sculpin, pumpkinseed & steehead. **Had the highest %age of signs**= white crappie, smallmouth, rainbow. One each bullhead, largemouth had more. **Had varying levels of signs**=black crappie, bluegill,catfish, chiselmouth, carp, pikeminnow, 2 app of sucker, whitefish. (Richter et al, 2006)

Rainbow Trout		110-140%	9-10 dy	0.25, 1.0, & 2.5m	10^{o}C			Laboratory tests. Static tests at 0.25m time to mortality ranged from longer than test duration of 6 dy at TDG less than 122% to 5.1 hr at 140% TDG. Mortality of fish exposed to 122% TDG in 1 m and 2.5 m volitional tests was 22% and 0%, respectively. Tests allowing use of depth significantly delayed onset of mortality and reduced cumulative mortality. Volitional tests support findings that depths of 2 m compensate for TDG up to 120%. (Antcliffe, BL et al, 2002)
Northern pikeminnow, bridgelip, longnose & largescale sucker, steelhead & walleye				Median: Steelhead 1.6 m Pikeminnow 2.0 m Bridgelip 2.8 m Walleye 3.7 m Longnose 5.2 m Largescale 6.8 m			Reduced growth was not associated with TDGS	All spp tested displayed median depths compensatory to TDG level well above 120%.The authors note a shift in the relative abundances of the 3 sucker species in Lake Rufus Woods since 1970. They suggest that the change might be associated with relative species-specific TDG sensitivity or with several other changes in environmental conditions of the lake. (Beeman et al, 2003).

<u>Fish</u> Peamouth Sucker Northern pikeminnow Smallmouth bass Threespine stickleback Sculpin Yellow perch Redside shiner Chiselmouth Pumpkinseed Bluegill Largemouth bass Common carp Crappie Bullhead Whitefish Sand roller Unidentified fish American shad Tench Walleye Banded killifish Dace Goldfish Lamprey Channel catfish White sturgeon Starry flounder <u>Invertebrates</u> Amphipoda Argulus Bryozoa Chironomidea Cladocera Coleoptera Copepoda Corbicula Corophium Culicidae Diptera Dolichopodidae Ephemeroptra Gastropoda Heleidae Hydracarina Hydrozoa Muscidae Mysid Nemeatoda Nemertean Oligochaeta Ostracoda Pacifastacus		At the end of the 4 yr study, TDG levels between 110 & 120% were examined to evaluate the effects of TDG below the waiver limit of 120% TDG.		Fish studies were conducted in water less than 3m deep in river reaches below Ice Harbor, Priest Rapids and Bonneville dams. Invertebrates were collected in depths up to 0.6 m.				Investigation observed 39,924 nonsalmonids fish. When TDG levels were below 120%m, GBD signs in fish were rare. The authors opined that the waiver limits of 115/120% were of little or no detriment to nonsalmonid fish. However, they did suggest that changing the waivers to allow TDG in excess of 120% would result in an increase in GBD. (Ryan, B.A., et al 2000)

Rainbow, brown, bull & cutthroat trout Mountain whitefish Northern Pikeminnow Largescale sucker				Fish used in this study were collecte d from near shore depths **‹2m**				Most of the tagged spp in this study had median and average depth distribution of about 2m or more, providing compensation for TDG in the range of 120% or more. “BD” defined as “uncompensated hyperbaric pressure of total dissolved gases”. The ntural behavior of the fish determines its vulnerability to GBD. The behavior of the fish in this study places them at depths and locations that reduce or eliminate exposure to supersaturation. The observed behavior explains the relatively low rates and minor severity of GBD observed in the fish collected in the shallow waters. (Weitkamp et al 2003a)
Rainbow Brown, bullhead Lake trout Cutthroat trout Kokanee Longnose &, Largescale s ucker Mtn whitefish N.pikeminnow Peamouth Yellow bullhead Tench Redside shiner Yellow perch Sm. mouth bass Fathead minnow								TDG levels in the Clark Fork River varied greatly over the years. In 1997 TDG was exceptionally high, between 143-158% for over a month, followed by a month greater than 127%. Inspite of this few resident fish showed any GBD when TDG was 125-130% of surface saturation. There is need for causiton in using results of laboratory and live-cage investigations to interpret conditions in the natural environment. Unlike most water quality issues, the depth distribution of the fish in the natural habitat greatly influences the biological effects of TDG. Intermittent exposure to 125-130% TDG has essentially no effect on resident fish. Intermittent exposure to 120-130% in 1998 and 2000 posed little risk to the fish...The data suggest that TDG levels below 125% do not result in a substantial incidence of GBD in fish. (Weitkamp et al 2003b)

Sucker Peamouth Stickelback Chinook salmon Sculpin N Pikeminnow Sm mouth bass Carp Coho salmon Crappie Redside ahiner Yellow perch Chiselmouth Killifish Walleye Bluegill Whitefish Lrg mouth bass Pumpkinseed Steelhead Goldfish Bullhead Am.shad Dace Starry flounder		Below Ice Harbor 130% mid-May-mid-June. Downstream Bonneville Rarely exceeded 120%		Fish studies were conducted in water less than 3m deep in river reaches below Ice Harbor, Priest Rapids and Bonneville dams. Invertebrates were collected in depths up to 0.6 m.				Below IHR TDG average 130% during period. GBD in resident fish averaged 15%. GBD incidence in net pens were 84% for fall Chinook and 16% for resident fish. Downstream of BON TDGrarely exceederd 120%and prevalence of GBD was 0.1% for resident fish and 0.0% for salmonids. (Schrank, B.P., et al, 1997)
AsianClam Carp Chinook salmon Chum “ Coho “ Crayfish Cutthroat trout Dragonfly larvae Killifish Sucker Sculpin Shiner Am. shad Sockeye fFounder Steehead Stickleback		Peak TDG reached 128% for four days. Most of the Spril-June period the TDG ranged from 103 to 122%, averaged approximately 112%.						17 species of fish and 3 of invertebrates were collected between river mile 62 and 228. External signs of GBD were infrequent. A low prevalence of GBD occurred in 6 of the 20 spp examined. There were no signs of GBD in invertebrates. GBD Signs were highest in the salmonids. (Toner, M.A. and E.M. Dawley1995)

Appendix B.

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Washington & Oregon State - Adaptive Management Team.

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